

# Can strange stars mimic dark energy stars?

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The possibility of strange stars mixed with dark energy to be one of candidates for dark energy stars is the main issue of the present study. Our investigation shows that quark matter is acting as dark energy after certain yet unknown critical condition inside the quark stars. Our proposed model reveals that strange stars mixed with dark energy feature not only a physically acceptable stable model but also mimic characteristics of dark energy stars. The plausible connections are shown through the mass-radius relation as well as the entropy and temperature. We particularly note that two-fluid distribution is the major reason for anisotropic nature of the spherical stellar system.

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Study on the different aspects of the quark matter is drawing it's attention among the astrophysicists and particle physicists. Bhattacharyya and his coworkers [1, 2, 3] proposed that after the few microsecond of big bang the universe undergoes through a quark gluon phase transition which may be a process of origin and survival of the quark matter. The nature of the confining force which triggered this phase transition is almost unknown. Witten [4] first considered that at the critical temperature  $T_c \simeq 200$  MeV a small portion of the colored objects like quark and gluon leaves hadronization through phase transition to form the colored particles called quark nuggets(QN). This QNs are made of  $u$ ,  $d$  and  $s$  quarks and have density few times higher than the normal nuclear density. These was further investigated by [5, 6, 7]. For both the cases in the compact stars and in the early universe Ghosh [8] investigated the role of quark matter in the phase transition. It is believed that the quark matter exists in the core of neutron stars [9], in strange stars [10] and as small pieces of strange matter [11]. Investigations by Rahaman et al. [12] and Brilenkov [13] lead to an interesting and important result that quark matter plays the role as dark energy on the global level. It is worth mentioning that for the last several years CERN LHC is trying to recreate the situation encountered before and early of the hadronization period, performing collisions of the relativistic nuclei [14].

Chapline [15] proposed that a gravitationally collapsing compact star which has mass greater than few solar mass, a quantum critical surface for space-time and an interior region consist of large amount of dark energy compared to the ordinary space-time can be defined as dark energy stars. He also predicted that this surface of compact dark energy stars is a quantum critical shell [16]. When an ordinary matter which have energy beyond the critical energy  $Q_0$  enters the quantum critical region, it decays into constituent products and corresponding radiation takes place outward direction perpendicular to that quantum critical surface. For the matter having energy  $< Q_0$  they can pass through that critical surface and

follow a diverging geodesics inside the stars. For the compact objects and compact stars at the center of galaxies the energy of the quarks and gluons inside the nucleons are higher than the critical energy  $Q_0$  [17]. According to Georgi-Glashow grand unified model nucleons decays in a process in which a quark decays into a positron and two antiquarks. So the observation of excess positron in the center of the galaxy may validates the presence of dark energy stars.

In the present article we have tried to investigate the possible connection between the proposed quark stars model mixed with the dark energy to the dark energy stars. Following the works of Rahaman et al. [12] and Brilenkov [13] we propose that quark matter is one of the possible candidates for dark energy. We are considering an anisotropic quark star model where we assume that the dark energy density is linearly proportional to the quark matter density. The proposed stellar configuration consist of two kind of fluids: (i) quark nuggets (QN), and (ii) dark energy having repulsive nature. We have avoided any interaction between the fluids for the simplicity of the model. To describe the equation of state (EOS) of the effective fluid of the stellar model we have used MIT bag EOS. It is worth mentioning that the anisotropy in compact stars may arise due to phase transition, mixture of two fluids, existence of type 3A superfluid, bosonic composition, rotation, pion condensation etc. at the microscopic level. In the present study of the proposed anisotropic two-fluid model we are adopting the following compact stars *PSR J1614-2230*, *Vela X-1*, *PSR J1903+327*, *Cen X-3* and *SMC X-4* as testing candidates.

To describe the interior of the relativistic compact stars mixed with dark energy we are considering following space-time metric

$$ds^2 = e^{\nu(r)} dt^2 - e^{\lambda(r)} dr^2 - r^2(d\theta^2 + \sin^2\theta d\phi^2), \quad (1)$$

where  $\nu$  and  $\lambda$  depends only on the radial coordinate  $r$ .

The energy-momentum tensors of the proposed two

fluid model are given by

$$\begin{aligned} T_0^0 &\equiv \rho_{eff} = \rho_q + \rho_{de}, \\ T_1^1 &\equiv -p_{reff} = -(p_{qr} + p_{der}), \\ T_2^2 &\equiv T_3^3 \equiv -p_{teff} = -(p_{qt} + p_{det}), \end{aligned} \quad (2)$$

where  $\rho_q$ ,  $p_{qr}$  and  $p_{qt}$  represent the quark matter density, radial pressure and tangential pressure respectively whereas  $\rho_{de}$ ,  $p_{der}$  and  $p_{det}$  represent respectively the dark energy density, radial pressure and tangential pressure within the stars. On the other hand, by  $\rho_{eff}$ ,  $p_{reff}$  and  $p_{teff}$  we represent respectively the effective energy density, radial pressure and tangential pressure of the matter distribution of the stellar system.

Now to solve the Einstein equations for our spherical distribution we consider the following *ansatz*: (i) the effective matter of the proposed star model obeys equation of state (EOS) of the phenomenological MIT bag model i.e.  $p_{reff} = \frac{1}{3}(\rho_{eff} - 4B_g)$ , where  $B_g$  is the bag constant, (ii) the dark energy radial pressure is related to the dark energy density as following  $p_{der} = -\rho_{de}$ , and (iii) the dark energy density is linearly proportional to the quark density, i.e.  $\rho_{der} = \alpha\rho_q$ , where  $\alpha$  is the proportionality constant and  $\alpha > 0$  which takes important role in determination of phase transition from the quark matter to the dark energy. Here the second *ansatz* represents the EOS of the matter distribution which is called ‘degenerate vacuum’ or ‘false vacuum’ [19, 20, 21, 22].

Let us now consider that the star has mass function as

$$m(r) = 4\pi \int_0^r \rho_{eff}(r) r^2 dr. \quad (3)$$

Following Mak and Harko [23] we are considering the quark matter density inside the stars can be expressed by the density profile given as

$$\rho_q(r) = \rho_c \left[ 1 - \left( 1 - \frac{\rho_0}{\rho_c} \right) \frac{r^2}{R^2} \right], \quad (4)$$

where  $\rho_c$  and  $\rho_0$  are respectively the quark matter central and surface density whereas  $R$  is the radius of the star.

Using Eq. 2 the effective matter density within the stars is given as

$$\rho_{eff}(r) = (1 + \alpha)\rho_c \left[ 1 - \left( 1 - \frac{\rho_0}{\rho_c} \right) \frac{r^2}{R^2} \right], \quad (5)$$

where the central and surface densities of the effective matter inside the stars are  $\rho_{effc} = (1 + \alpha)\rho_c$  and  $\rho_{eff0} = (1 + \alpha)\rho_0$  respectively.

The effective gravitation mass of the stars can be found using Eqs. (3) and (5) as

$$M = \frac{4}{15} (1 + \alpha) (2\rho_c + 3\rho_0) \pi R^3. \quad (6)$$

Considering that radial pressure is zero at the surface we find from the *ansatz* (i) and Eq. (5) as follows

$$\rho_0 = \frac{4B_g}{1 + \alpha}. \quad (7)$$

Now by using Eqs. (6) and (7), along with the first *ansatz*, one can find the anisotropy of the system of the

proposed model as given by

$$\begin{aligned} \Delta(r) &= p_{teff} - p_{reff} \\ &= \frac{2}{3} \frac{\left\{ \left( \frac{1}{2} c_1^2 r^4 + \frac{13}{10} R^2 c_1 c_2 r^2 + c_3 R^4 \right) \pi + \frac{3}{16} R^2 c_1 \right\} r^2}{\left\{ \frac{3}{5} (\rho_c - \rho_0) r^2 - \rho_c R^2 \right\} (\alpha + 1) r^2 \pi + \frac{3}{8} R^2 R^2}, \end{aligned} \quad (8)$$

where  $c_1 = (\rho_0 - \rho_c)(\alpha + 1)$ ,  $c_2 = (\alpha + 1)\rho_c - \frac{28}{13}B_g$  and  $c_3 = [(\alpha + 1)\rho_c - 2B_g][(\alpha + 1)\rho_c - B_g]$ .

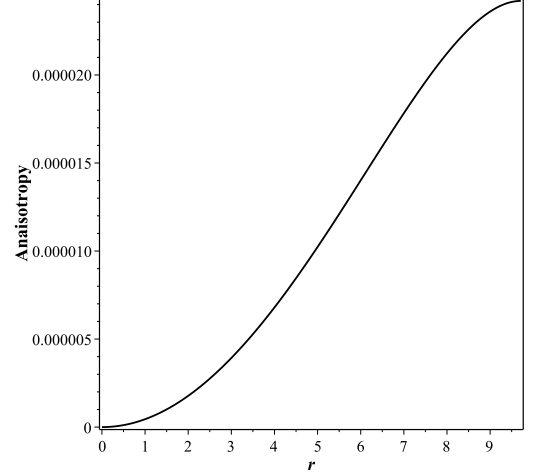


FIG. 1: Variation of anisotropy ( $\Delta$ ) with the radial coordinate for the different values of  $\alpha$  for the strange star *SMC X-4*, where  $B_g = 83 \text{ MeV}/(fm)^3$ ,  $R = 9.711 \text{ km}$  and  $M = 1.29 M_\odot$

The above physical parameter  $\Delta(r)$  [see Fig. 1], following the method of [18] and after using Eqs. (6) and (7), gives the maximize anisotropy at the surface as

$$\begin{aligned} \Delta'(r)|_{r=R} &= \frac{1}{12 R^3 (-R + 2M)^2 \pi} \left[ 80 R^4 \pi B_g \right. \\ &\quad \left. + 240 \pi B_g R^2 M^2 - 304 \pi R^3 B_g M - 1280 \pi^2 R^5 B_g^2 M \right. \\ &\quad \left. + 30 M^2 - 15 R M + 1024 \pi^2 R^6 B_g^2 \right] = 0. \end{aligned} \quad (9)$$

Solving Eq. (9), after using the values of different observational mass of the different stars and with the choice of the value of bag constant as  $83 \text{ MeV}/(fm)^3$  [24], we get different values of  $R$  for a star. We choose only that value of  $R$  which is physically valid and consistent with the Buchdahl condition [25] and find that anisotropy is maximum at the surface of the stars. The central pressure ( $p_{reff} = p_{teff}$ ) can shown to be turned out as  $5.654 \times 10^{34} \text{ dyne/cm}^2$  for *SMC X-4*.

According to Buchdahl [25] the maximum allowed mass-radius ratio for a static spherically symmetric compact star is  $2M/R \leq 8/9$ . Later Mak and Harko [26] came up with the more generalized expression for the same mass-radius ratio. Now in our model the effective gravitational mass which is defined in Eq. (6) given as  $M = \frac{4}{15} (1 + \alpha) (2\rho_c + 3\rho_0) \pi R^3$ . The variation of the effective mass with the radius of the stars has shown in

FIG. 2.

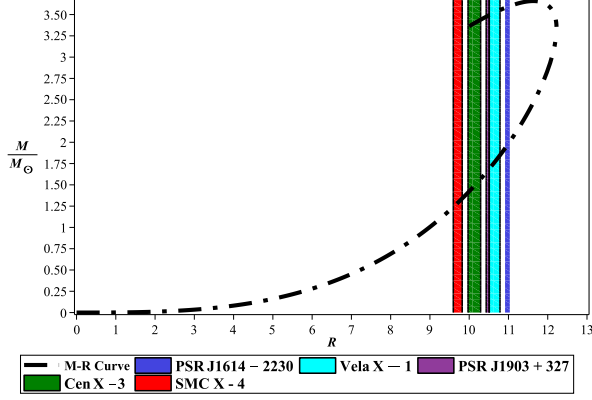


FIG. 2: Effective mass-radius ( $M - R$ ) curve for the different strange stars having  $B_g = 83 \text{ MeV}/(fm)^3$ . The stars represented by the  $M - R$  curve after it passes the maximum mass point are not stable. We find the value of maximum effective mass and maximum radius are  $3.66 M_\odot$  and  $R_{max} = 12.225 \text{ km}$  respectively

Now the maximum value of the effective mass  $M_{max}$  of the stars corresponding to  $\rho_c|_{M_{max}}$  can be derived using the equation  $\frac{dM}{d\rho_c} = 0$ . Similarly using the equation  $\frac{dR}{d\rho_c} = 0$  we can derive the maximum radius  $R_{max}$  for  $\rho_c|_{R_{max}}$ . The value of the maximum effective mass and radius are  $3.66 M_\odot$  and  $12.225 \text{ km}$  respectively.

To derive entropy and temperature of the stellar model we are taking help of the Gibbs relation,  $p_{eff} + \rho_{eff} = sT + n\mu$ , where  $s(r)$  is the local entropy density,  $T(r)$  is the local temperature,  $\mu$  is chemical potential and  $n$  is the number density of matter distribution inside the ultra-dense stars. Let consider for the simplicity, the matter distribution inside the stellar configuration is isotropic in nature and the value of  $\mu$  is negligible. Hence the Gibbs relation become

$$p_{eff} + \rho_{eff} = sT. \quad (10)$$

Now using first and second law of thermodynamics along with the first *ansatz* we have following relation

$$ds = \frac{V}{T} d\rho_{eff} + \frac{4}{3} \frac{(\rho_{eff} - 4B_g)}{T} dV, \quad (11)$$

where  $V$  is the volume of the stellar configuration. As  $S = S(\rho, V)$  and  $dS$  is perfect differential hence one may find from Eq. (11)

$$\rho_{eff} = \beta T^4 + B_g, \quad (12)$$

where  $\beta$  is the integrating constant and having value as  $\sigma = \frac{1}{4}\beta$ . Here  $\sigma$  represents the famous Stefan constant.

Hence, after some manipulation one can find the entropy density as follows

$$s = \frac{4}{3} \beta T^4, \quad (13)$$

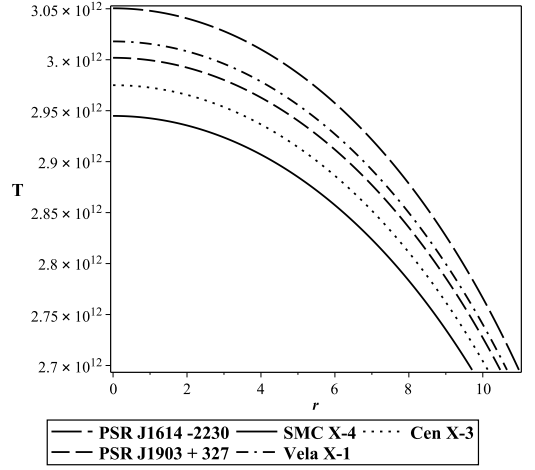


FIG. 3: Variation of temperature ( $T$ ) with the radial coordinate for the strange star *SMC X-4*, where  $B_g = 83 \text{ MeV}/(fm)^3$ ,  $R = 9.711 \text{ km}$  and  $M = 1.29 M_\odot$

which provides a basic idea about the total entropy of the compact stellar system.

Variation of the temperature in the interior region of the different strange star candidates are shown in the FIG. 3. From the figure we find that the temperature in the central region is maximum and it decreases with the radial coordinate and become minimum at the surface which is physically acceptable. For the stellar configurations we find the temperature is higher than the Fermi melting point ( $0.5 - 1.2 \times 10^{12} \text{ K}$ ) of quark. Hence all the quark matters in the ultra dense compact stars remains in the form of quark-gluon plasma.

For the anisotropic static stellar configuration though the radial pressure is zero at the surface but the tangential pressure is not zero simultaneously. However, as the radial pressure is continuous at the boundary we are already satisfying Synge's junction condition [27] in the case of static spherical symmetry. In the boundary the interior solution and the exterior Schwarzschild solution should match to satisfy the fundamental junction condition. The metric coefficients are continuous at  $S$  where  $r = R = \text{constant}$ . The second fundamental form is also continuous on the boundary surface. Now the intrinsic stress-energy tensor  $S_j^i = \text{diag}(-\sigma, \mathcal{P})$  at the boundary surface  $S$  (where  $r = R$ ) can be defined as the surface stresses, i.e the surface energy  $\sigma$  and surface tangential pressures  $p_\theta = p_\phi \equiv \mathcal{P}$  which are in the present situation given as  $\sigma = 0$  and  $\mathcal{P} = 0$ . So the complete spacetime is given by our interior metric and the exterior Schwarzschild metric which are matched smoothly on the boundary  $S$ .

Under the proposed model we have presented a data set for the physical parameters of some strange stars in TABLE 1.

Let us highlight the major results of the proposed

TABLE I: Physical parameters as derived from the proposed model

Strange Stars	Observed Mass ( $M_{\odot}$ )	Observed Mass (km)	Predicted Radius (km)	$\rho_c$ ( $gm/cm^3$ )	$p_{ceff}$ ( $dyne/cm^2$ )	$\frac{2M}{R}$	$Z$	$T_c$ ( $K$ )
<i>PSR J 1614 – 2230</i>	$1.97 \pm 0.04$	$2.9057 \pm 0.059$	$10.977 \pm 0.06$	$8.756 \times 10^{14}$	$8.523 \times 10^{34}$	0.53	0.46	$3.051 \times 10^{12}$
<i>Vela X – 1</i>	$1.77 \pm 0.08$	$2.6107 \pm 0.118$	$10.654 \pm 0.14$	$8.486 \times 10^{14}$	$7.603 \times 10^{34}$	0.49	0.40	$3.018 \times 10^{12}$
<i>PSR J 1903 + 327</i>	$1.667 \pm 0.021$	$2.4588 \pm 0.03$	$10.473 \pm 0.037$	$8.352 \times 10^{14}$	$7.167 \times 10^{34}$	0.47	0.37	$3.002 \times 10^{12}$
<i>Cen X – 3</i>	$1.49 \pm 0.08$	$2.1977 \pm 0.118$	$10.136 \pm 0.16$	$8.082 \times 10^{14}$	$6.441 \times 10^{34}$	0.43	0.33	$2.975 \times 10^{12}$
<i>SMC X – 4</i>	$1.29 \pm 0.05$	$1.9027 \pm 0.073$	$9.711 \pm 0.11$	$7.813 \times 10^{14}$	$5.654 \times 10^{34}$	0.39	0.28	$2.945 \times 10^{12}$

model here: (i) under certain critical condition the quark matter is converting into the dark energy; (ii) with the presence of dark energy inside the strange stars, they behave like dark energy stars; (iii) the high temperature distribution ( $>$ Fermi melting point of quark) inside the stars confirms the presence of quark matter in the form of quark-gluon plasma; (iv) all the physical and structural features of the proposed ultra-dense strange star model match well with the dark energy stars as suggested by Chapline [15]; and (v) some of the physical tests, viz. the energy conditions, TOV equations and sound speed constraint are found to be satisfied in the presented model and thus the model has stable configuration in all respect. According to Herrera [28] and Andréasson [29] to form physically acceptable matter distribution the quark matter also have to maintain the condition  $0 \leq v_{sqr}^2 \leq 1$ , where  $v_{sqr}$  represents the radial sound speed of the quark matter. This leads to the result that the acceptable value of  $\alpha$  lies in the range  $0 \leq \alpha \leq \frac{1}{2}$ .

However, some shortcomings of the proposed model also are there as follows: (i) we proposed that quark matter is converting into dark energy, but cannot predict under which condition this is actually happening, and (ii) in the range  $0 \leq \alpha \leq \frac{1}{2}$ , we consider  $\alpha$  as a constant term and hence it is not clear whether the dark energy in the stellar configuration remains constant all the time or varies with the time within the provided range of  $\alpha$ . In connection to this comment one can specifically note that in the present model the metric coefficients are considered as independent of time. However, all these issues can be considered in a future investigation.

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- [1] A. Bhattacharyya, *et al.*, Nucl. Phys. A **661**, 629 (1999).
- [2] A. Bhattacharyya, *et al.*, Phys. Rev D **61**, 083509 (2000).
- [3] A. Bhattacharyya, *et al.*, Pramana **60**, 909 (2003).
- [4] E. Witten, Phys. Rev. D **30**, 272 (1984).
- [5] A. Applegate and C.J. Hogan, Phys. Rev. D **31**, 3037, (1985).
- [6] E. Farhi and R.L. Jaffe, Phys. Rev. D **30**, 2379 (1984).
- [7] D. Chandra and A. Goyal, Phys. Rev. D **62**, 063505 (2000).
- [8] S. Ghosh, Astrophysics of Strange Matter, Plenary Talk at 2008 Quark Matter, Jaipur, India; arXiv:astro-ph/0807.0684.
- [9] M.A. Perez-Garcia, J. Silk and J.R. Stone, Phys. Rev. Lett. **105**, 141101 (2010).
- [10] J.J. Drake, *et al.*, Astrophys. J. **572**, 996 (2002).
- [11] J. Madsen, Lect. Notes Phys. **516**, 162 (1999).
- [12] F. Rahaman, *et al.*, Phys. Lett. B **714**, 131 (2012).
- [13] M. Brilenkov, *et al.*, JCAP **08**, 002 (2013).
- [14] M.I. Adamovich, *et al.*, Phys. Lett. B **263**, 539 (1991).
- [15] G. Chapline : arXiv: astro-ph/0503200.
- [16] G. Chapline, E. Hohlfield, R.B. Laughlin and D. Santiago, Phil. Mag. B, **81**, 235 (2001).
- [17] J. Barbieri and G. Chapline, Phys Lett. B, **590**, 8 (2004).
- [18] D. Deb, *et al.*, arXiv:1606.00713 (2016).
- [19] C.W. Davies, Phys. Rev. D **30**, 737 (1984).
- [20] J.J. Blome and W. Priester, Naturwiss. **71**, 528 (1984).
- [21] C. Hogan, Nat. **310**, 365 (1984).
- [22] N. Kaiser and A. Stebbins, Nat. **310**, 391 (1984).
- [23] M.K. Mak and T. Harko, Chine. J. Astron. Astrophys. **2**, 248 (2002).
- [24] F. Rahaman, *et al.*, Eur. Phys. J. C **74**, 3126 (2014).
- [25] H.A. Buchdahl, Phys. Rev. D **116**, 1027 (1959).
- [26] M.K. Mak and T. Harko, Proc. R. Soc. A **459**, 393 (2003).
- [27] S. O'Brien S. and J.L. Synge, Commun. Dublin Inst. Adv. Stud. A. **9** (1952).
- [28] L. Herrera, Phys. Lett. A **165**, 206 (1992).
- [29] H. Andréasson, Commun. Math. Phys. **288**, 715 (2009).